Matching from Merge to Cooling

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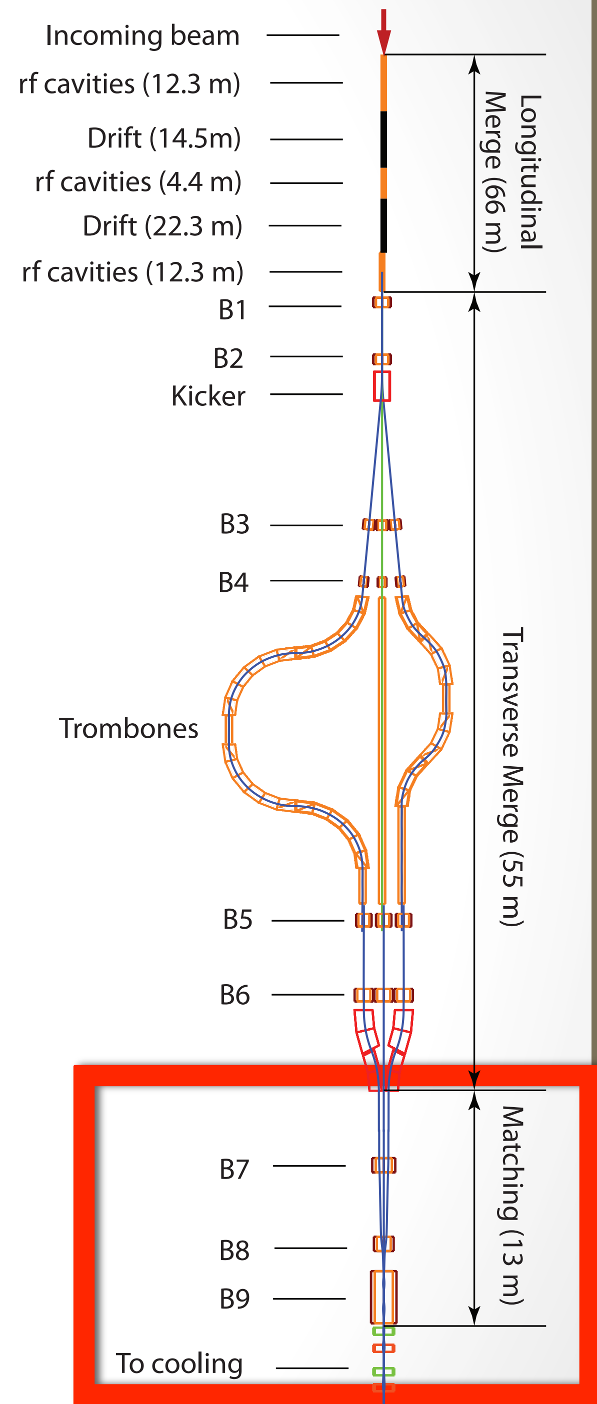
Reminder: Whole Merge Scheme

The bunch merger has been simulated, from longitudinal merge to the end of the funnel.

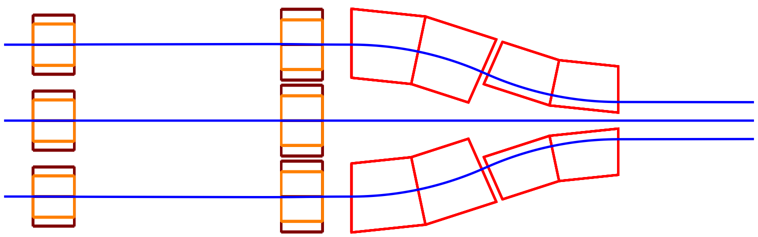
A matching is needed for injection to later cooling channel.

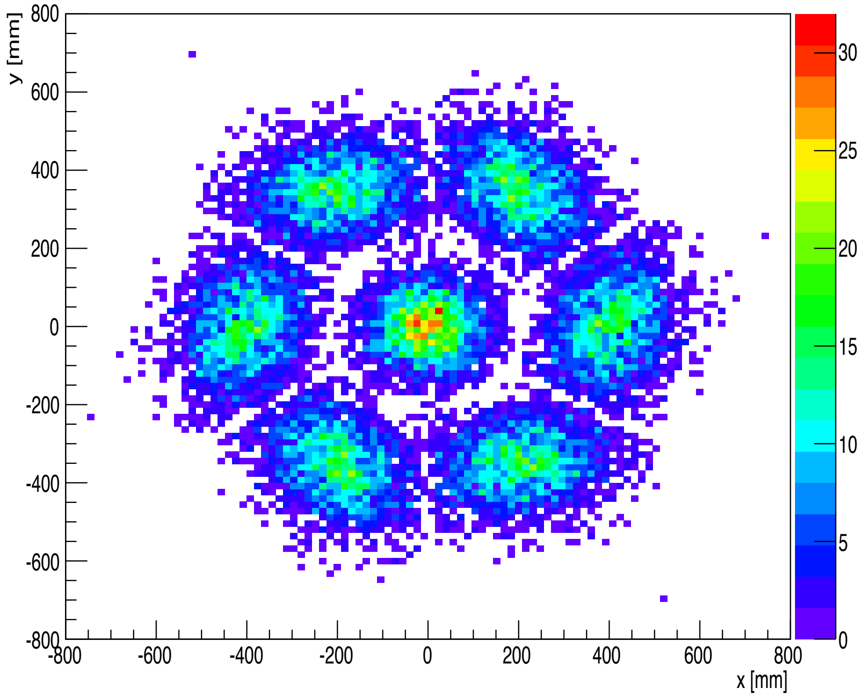
Two solenoids (B7 and B8) are used to reduce the transverse beam size, and a longer solenoid to match the field to cooling channel.

Longitudinal matching not considered…



Beam after funnel





- The beam has a big transverse size. β=22m
  - Later cooling channel requires 0.6m
- The bunch after funnel is not in solenoid magnet.
  - Later cooling channel has alternating magnetic field.

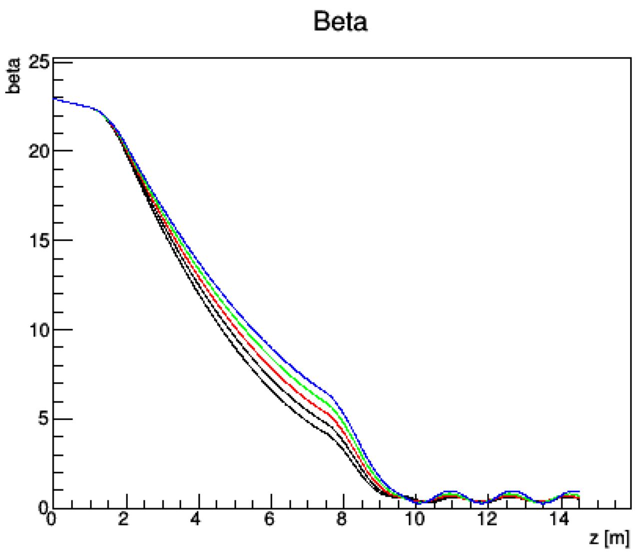
B7 and B8

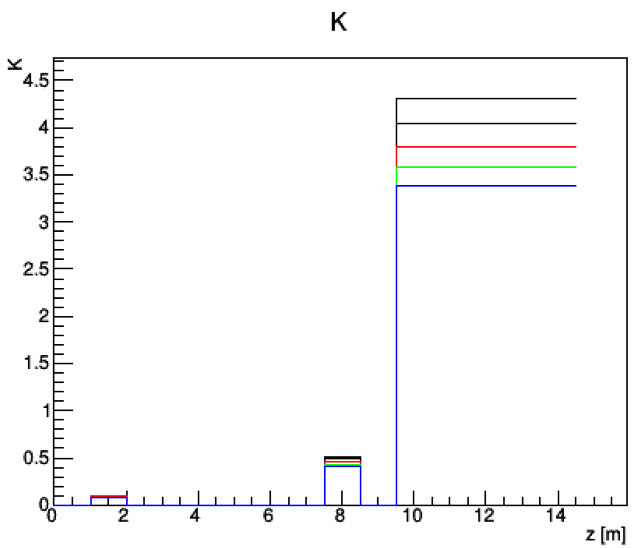
- ***Goal*** : matching a beam with β =22m and α =0 in zero B field to a straight 2.6 T solenoid magnet.
- ***Method***: define χ ,

$$\chi^2 = \sum_{p_i} [(\alpha(p_i)^2) + (\frac{\beta(p_i) - \beta_0(p_i)}{\beta_0(p_i)})^2]$$

and propagate Courant-Snyder parameters and change the positions and strengths of B7 and B8 to minimize χ

- ***Result:***





B9

- Goal: matching the bunch to the alternating field.
- Method: strength is fixed to 2.6 T, parameters to optimize are: length and position -> by hand.

- Result: Length=3.65m,

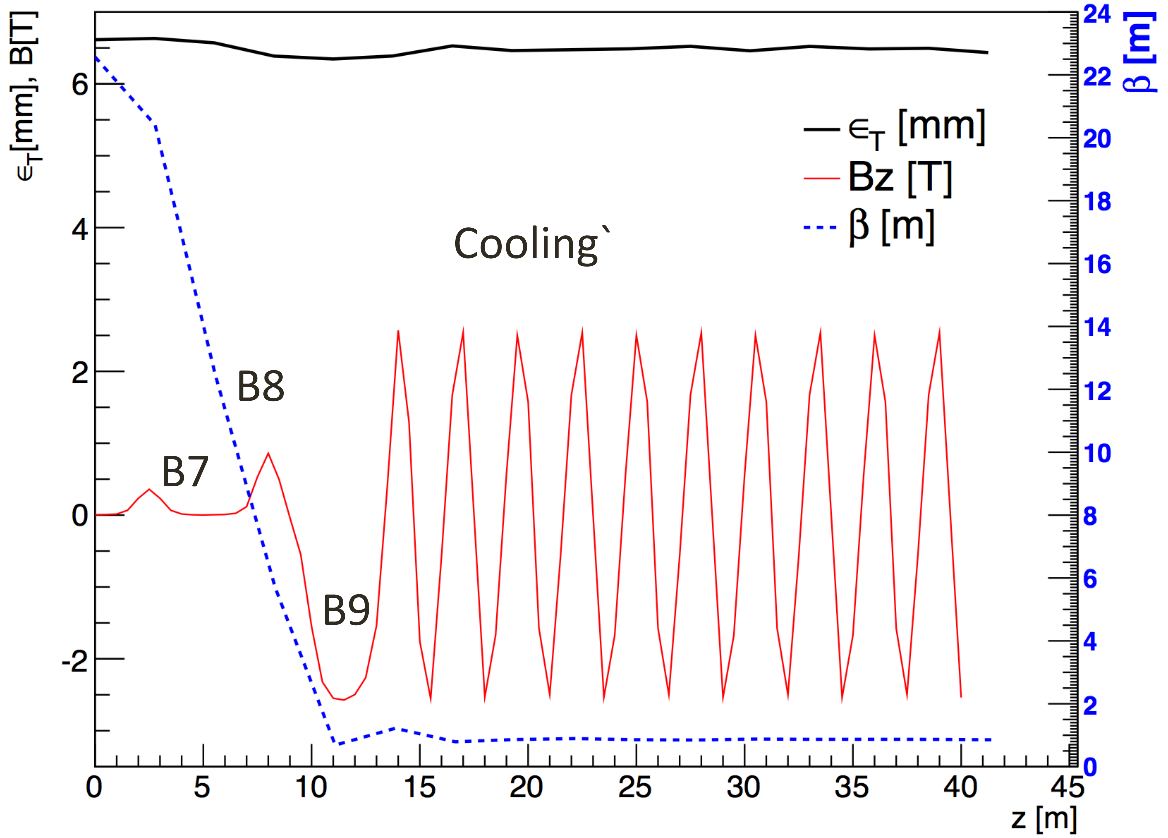
  Gap between B9 and cooling is 1.5m

Results

Transverse emittance conserves at 6.5mm.

β reduced to 0.6m.

Transmission > 99%



Phase Rotation for Intense Low-energy Muon Beams

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May 19, 2015

Useful low energy muons

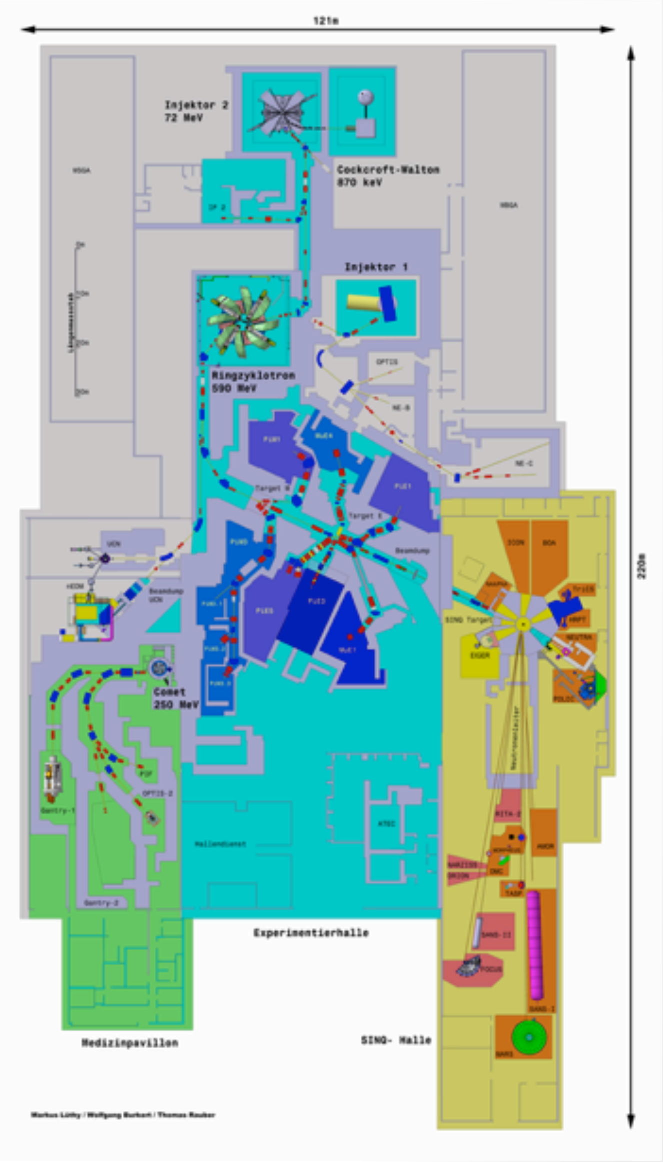
- **Rare decay searches**: Mu2e, Mu3e, MEG…
- **Muonium experiments**: $Mu-\overline{Mu}$ conversion, muonium spectroscopy, muonium decay, muonium gravity, muonic hydrogen...
- **Experiments and Applications**: muon EDM, g-2, muon catalyzed fusion, MuSun, Muon spectroscopy···
  - More than **200 experiments** are carried out at the muon beamlines at PSI **each year**!
- **All these experiments need high statistics!**

Where are muons produced?

- **Institutes**: PSI, ISIS, Triumf, JPAC, (Fermilab?)
- **Method**: Protons hitting targets

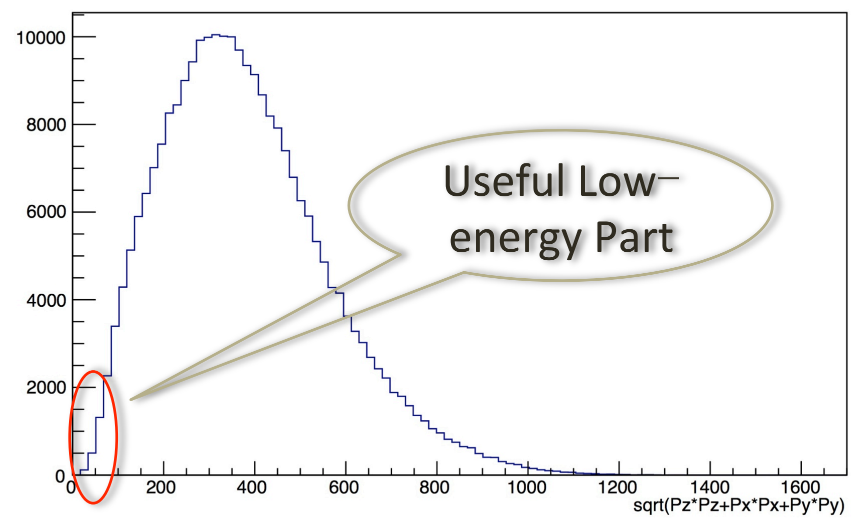
How muons are produced

- Intense proton beams hitting on thin targets, upstream of spallation targets.
- Two type of muons are produced: SURFACE muon and CLOUD muon
  - SURFACE muons: Pions decay on the surface of the target
  - CLOUD muons: Pions decay in flight
- Only a few percent of the primary proton beam is used for producing muons.



Cloud muon

- A typical cloud muon beam has a momentum peak around several hundreds MeV/c.
- Large momentum spread.
- High yield up to 0.02 muon per GeV proton at target.



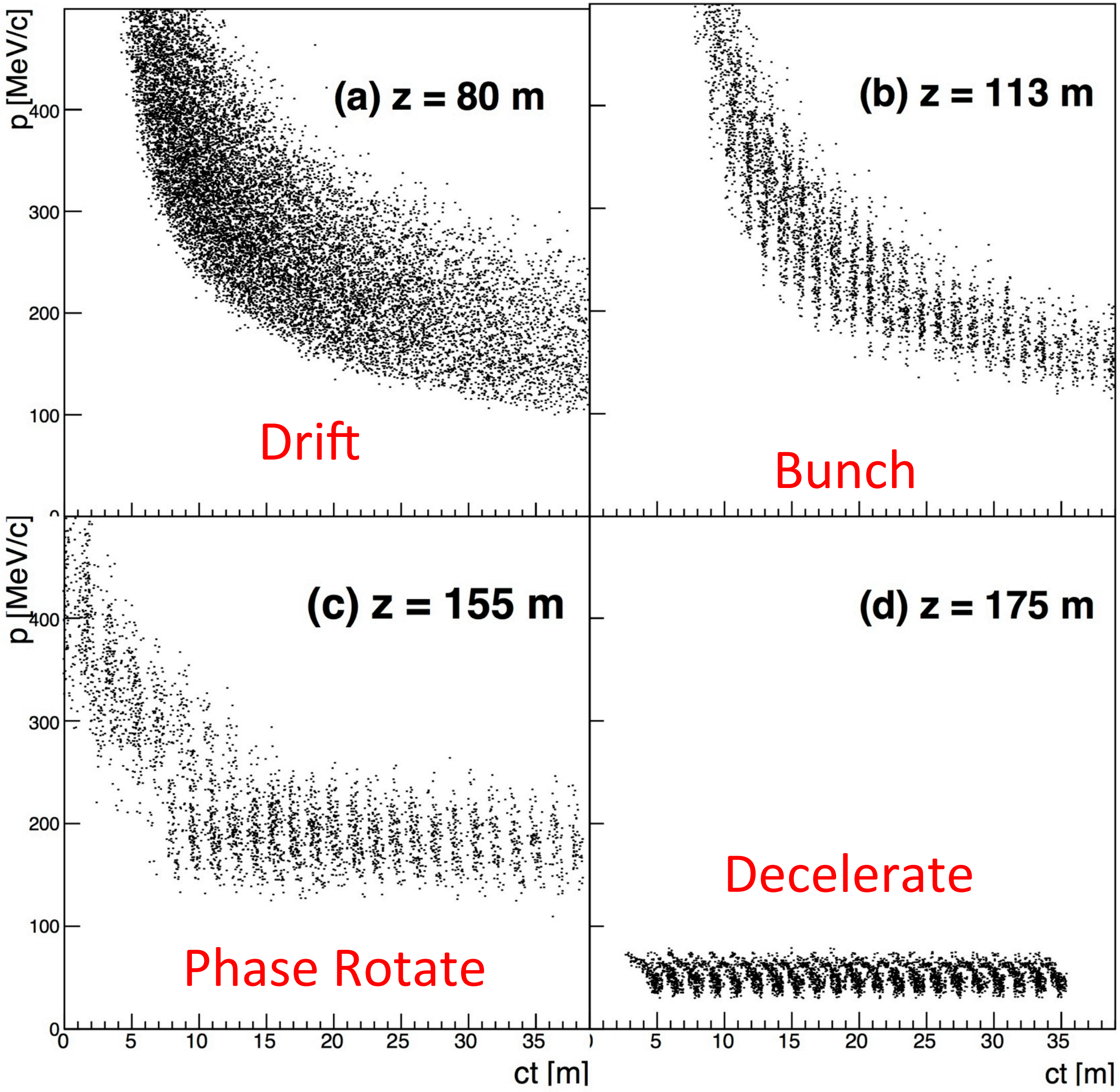
Typical momentum distribution of the initial pions.

How to make use of them?

Phase Rotation Technique

- Originally designed for the Neutrino Factory front end.
- Consists of four sections:
  - **Decay and drift**: to form a momentum-time correlation for the muon beam.
  - **Bunching**: to bunch the muons to a string of bunches.
  - **Phase rotation:** to rotate the bunches in longitudinal phase space so that they reach the same equilibrium momentum.
  - **Deceleration:** to decelerate the muons further to low energy

No muon cooing is involved !

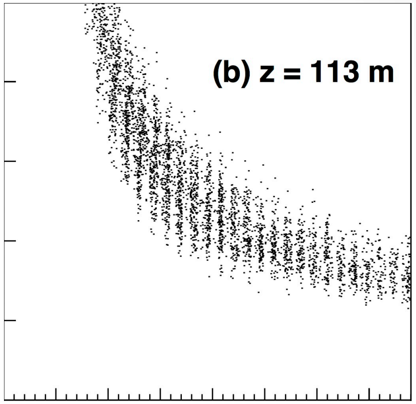


p [MeV/c]
400
300
200
100
0
(a) z = 80 m
Drift
(b) z = 113 m
Bunch
(c) z = 155 m
Phase Rotate
(d) z = 175 m
Decelerate
0
5
10
15
20
25
30
35
ct [m]

Decay and Drift

- Goal: to obtain a momentum-time correlation.
- The solenoid magnetic field tapers from high field capture region to 1.5 T.

Bunching



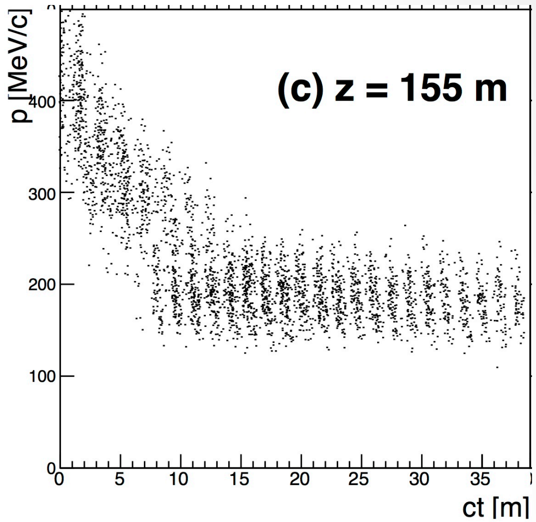
- Bunch the muons so that rf systems can be used for later phase rotation and deceleration.
- A series of cavities with various frequencies are used.
- Frequencies of the cavities are set to divide the beam into bunches with spaces of 0.94m by:

$$N_B \lambda_{\mathrm{rf}}(s) = N_B \frac{c}{f_{\mathrm{rf}}(s)} = s\left(\frac{1}{\beta_{N_B}} - \frac{1}{\beta_0}\right),$$

- The rf gradient is increased from cell to cell along the buncher gradually to enable an adiabatic capture of the muons:

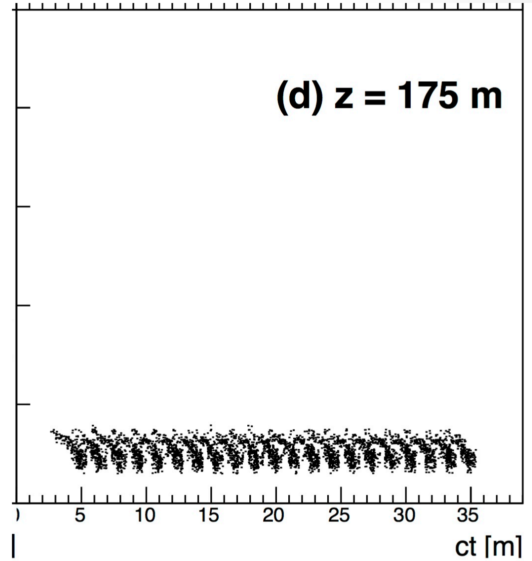
$$V_{\mathrm{rf}}(z) \approx 9 \frac{z}{L_B} \mathrm{MV/m},$$

Phase Rotation



- Rotate the bunches in longitudinal phase space
- The rf bunch spacing between the bunches is shifted away from the integer N_B , by an increment, δN_B , and phased so that the high-energy muons are decelerated to reach the same energy (150 MeV/c) as the reference particle.
- The rf gradient is 13 MV/m in 0.5m long rf cavities within 0.75 m long cells.

Deceleration



- Deceleration is done in five sections with drifts and rf cavities with a frequency of 201.25 MHz.

- Deceleration takes 20 m to decrease the momentum to less than 75 MeV/c.

- The bunch emittance is large after phase rotation, deceleration is inefficient. Only 20% muons are decelerated to low-energy.

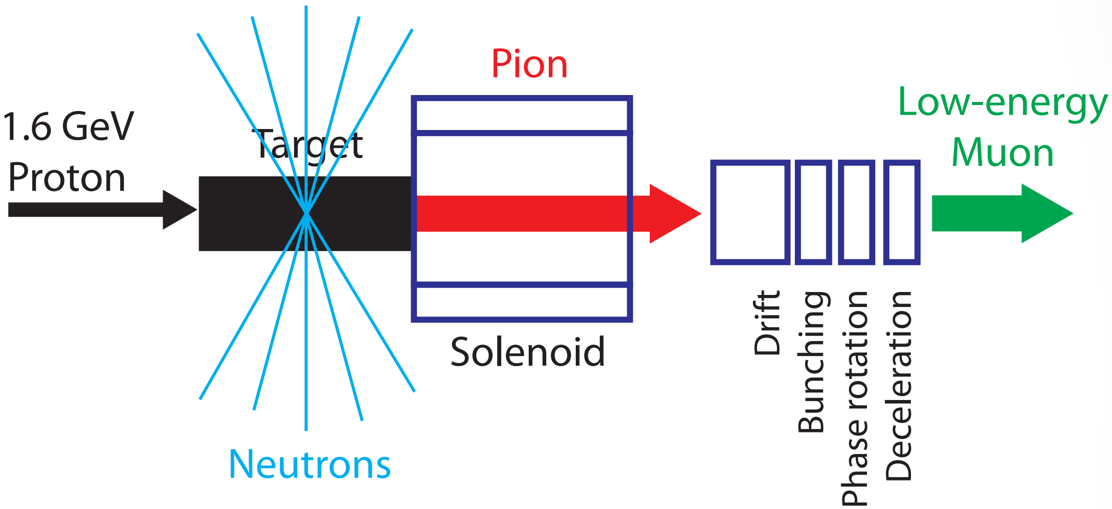
- Further optimization is needed. Induction linac will be considered in later work.

Application on Mu2e

- Efficiency of the Drift-Bunching-PhaseRotation-Deceleration channel is >10%.
- With a optimized target scheme which captures 0.02 pions per GeV proton, and a proton driver of 8 GeV, the intensity of the output low energy muon beam can reach above 0.016 muons per proton, which is already one order of magnitude higher than the current Mu2e design at Fermilab.
- Further optimization will focus on phase rotation for lower-energy muons and the deceleration channel.

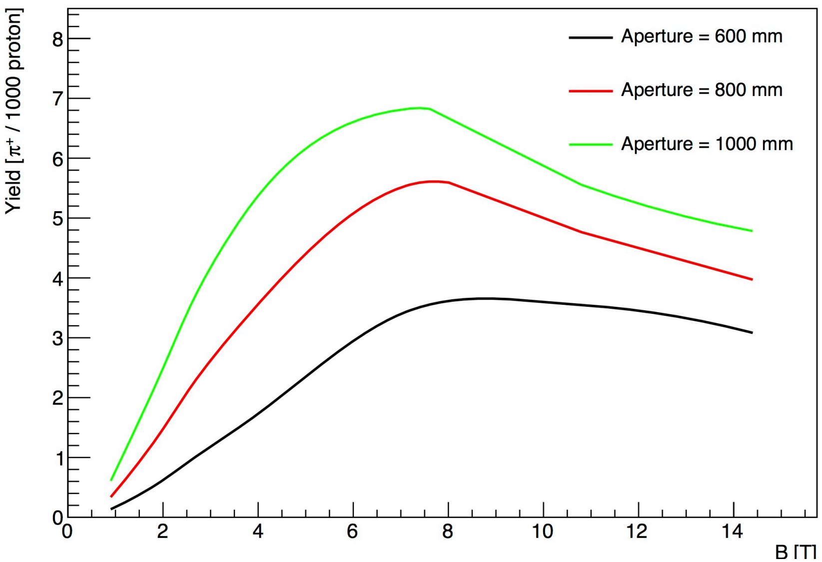
Another Example: Chinese Spallation Neutron Source

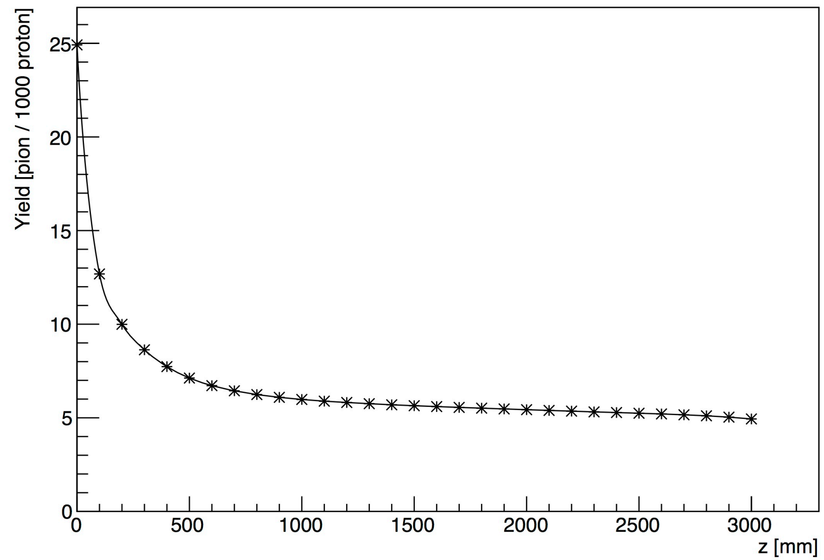
Intensity of pions after the spallation targets are high, because of high proton power.



- Put collecting solenoid after the spallation target, to minimize the influence on neutron production.
- Use the phase rotation technique to reduce the energy of the cloud muons.

Collecting





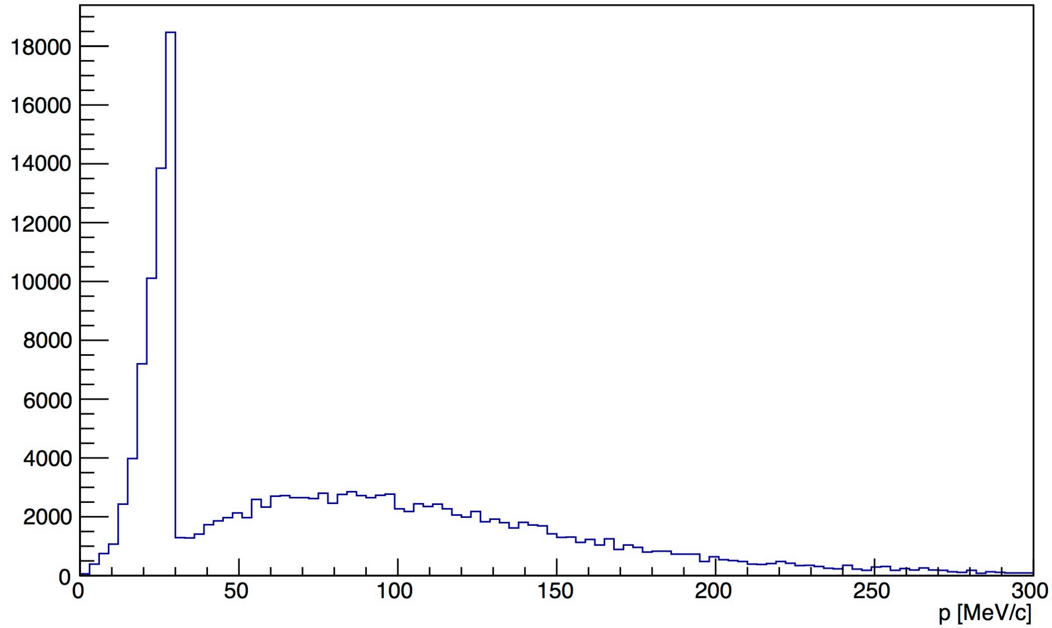
- A solenoid magnetic field of 7 T with a large aperture will collect the pions most efficiently.
- About 80% of the pions are lost in the first half meter.
- Better collection will be investigated by using toroidal field.
- With an aperture of 0.8 m the pion yield can reach 0.006 pion/proton

Low-energy Muon yield

- After the phase rotation and deceleration, the yield of the low-energy muons are 6 muons per 10,000 protons.
- This efficiency is low, due to the target geometry and the limit on the position of the collecting solenoid, however…
- With the 500 kW proton driver, the intensity of the output muons can reach 3*10^12 muons per second, which is two orders of magnitude higher than the current Mu2e design.

- And, this is a by-product of a spallation source!

Surface Muon

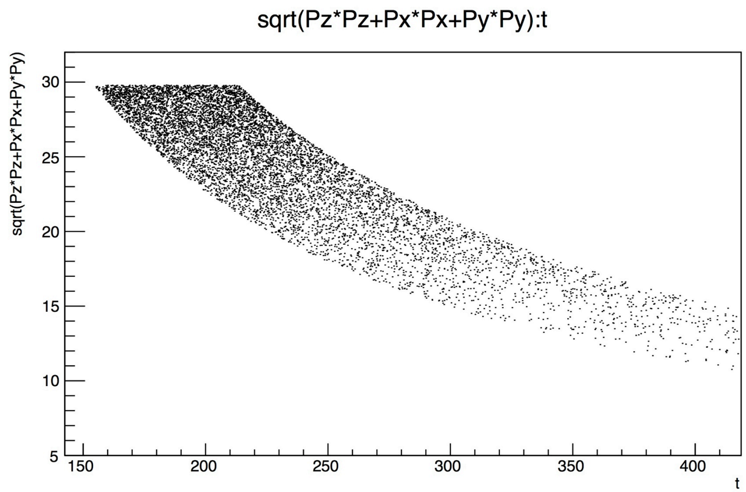


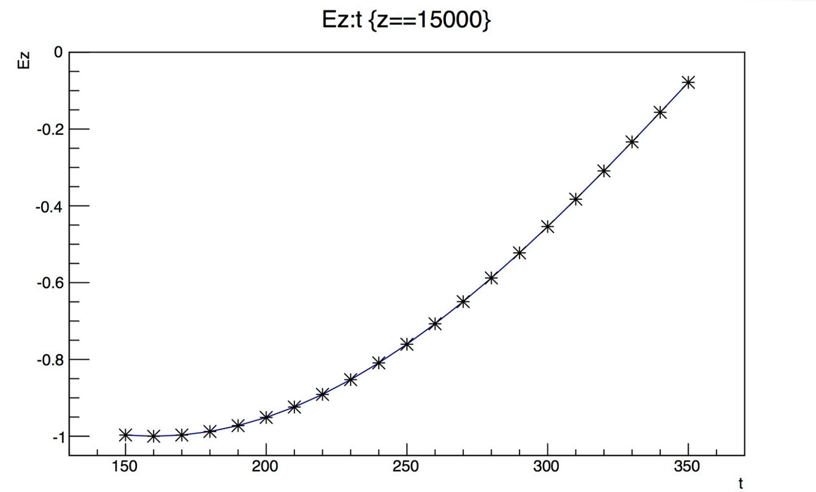
- Sharp peak at 30 MeV/c.
- Fully polarized beam.
- Various applications when slowed down to keV and eV energy range.

Deceleration options

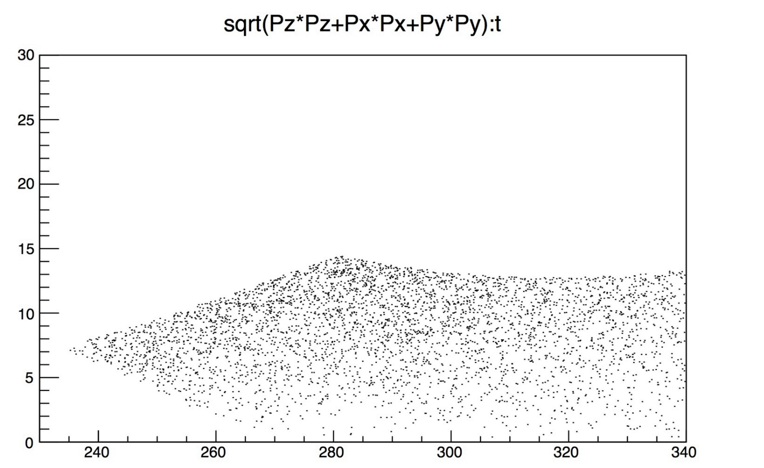
- The phase rotation technique can be applied to slow down surface muons with higher efficiency, because lower-energy muons requires less rf cavities to bunch and decelerate.
- Induction linac is more efficient,　and easier…

Using induction linac



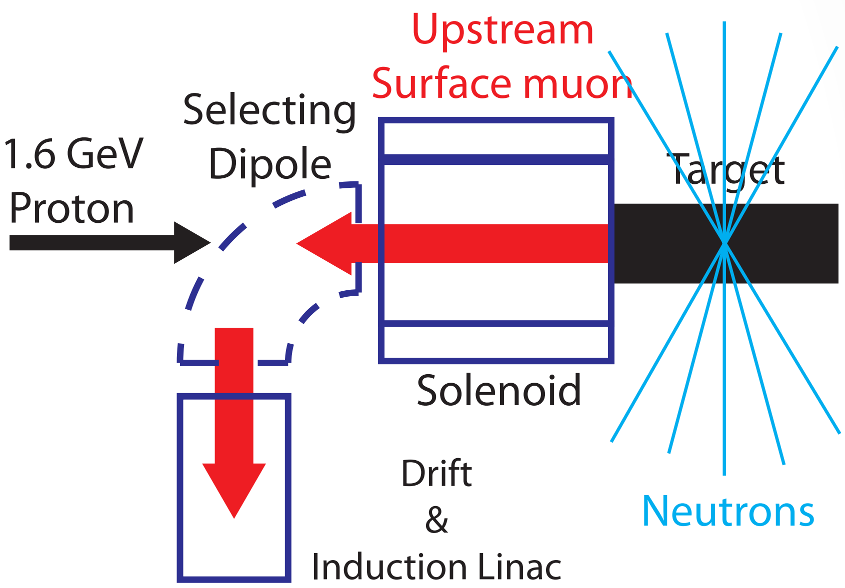


- Drift of 15 m.
- Maximum field 1 MV/m
- Rising time 200 ns.
- In 4m, mouns are slowed down to 10 MeV/c, which can be followed by Frictional cooling.
- Efficiency > 70% !
- A lot can be improved!



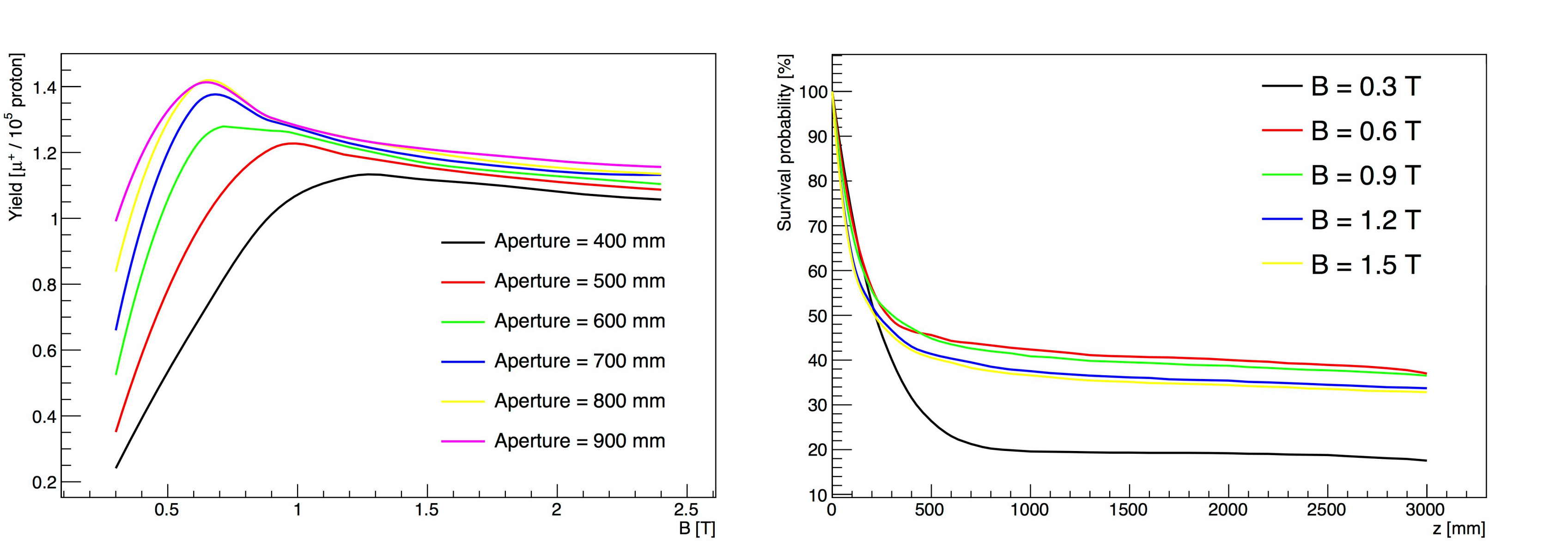
Example： CSNS

Surface muon rate is high at the back side of the spallation neutron target.



- Collect surface muons at the backside of the spallation target.
- After the drift channel, use induction linac to slow muons down.

Collecting solenoid



- A solenoid of 0.6 T with a large aperture has the highest yield. 60% muons lost in the first half meter.
- Improvement can be made by using toroidal field.

Estimation on slow muon intensity

- 0.6m aperture with 0.6T field yields 1.3 surface muons per 100,000 initial protons.
- With 500kW proton beam, a surface muon beam of 6.5*10^10 mu+/s can be reached at the end of the collecting solenoid.
- Considering deceleration by induction linac with an efficiency of 70%, 4.5*10^10 mu+/s are obtained with energy lower than 500 keV.
- Frictional cooling can be implemented to finally transform the muons to slow muons. (Efficiency should be larger than 1%)
- Slow muon rate on the order of 10^8 mu+/s can be expected, which is 4 orders of magnitude higher than current highest rate.

Summary

- We outline a phase rotation concept for decelerating muons for various experiments and applications.
- Two methods are presented with preliminary simulations.
- For higher-energy cloud muons, we use the front-end concept of a Neutrino Factory to phase rotate and decelerate the muons to lower than 75 MeV/c, with an efficiency higher than 10%.
- For surface muons we use induction linacs to slow down the muons to low energy with an efficiency higher than 70%
- Possible application of these methods are presented. Significantly high rate of low-energy muon can be expected.